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Passive Heat Removal Characteristics of SMART

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Abstract

A new advanced integral reactor of 330 MWt thermal capacity named SMART (System-Integrated Modular Advanced Reactor) is currently under development in Korea Atomic Energy Research Institute (KAERI) for multi-purpose applications. Modular once-through steam generator (SG) and self-pressurizing pressurizer equipped with wet thermal insulator and cooler are essential components of the SMART. The SMART provides safety systems such as Passive Residual Heat Removal System (PRHRS). In this study, a computer code for performance analysis of the PRHRS is developed by modeling relevant components and systems of the SMART. Using this computer code, a performance analysis of the PRHRS is performed in order to check whether the passive cooling concept using the PRHRS is feasible. The results of the analysis show that PRHRS of the SMART has excellent passive heat removal characteristics.

1. Introduction

The SMART is an integral type reactor with a thermal capacity of 330 MWt[1]. The major components of SMART such as modular once-through helical SG, self-regulating pressurizer, and canned motor main circulation pump are integrated into the reactor vessel. The concept of cold pressurizer is applied to the SMART and the pressurizer is equipped with wet thermal insulator and cooler. Modeling of once-through SG and cold pressurizer was developed and optimized sizing of SG and pressurizer cooler was performed[2]. The integral type reactor provides high flow rate of natural circulation of the coolant for the core due to the small system resistances and a relatively slow progression of transients due to the relatively large mass of primary coolant. In order to prevent progression of emergency situation into accidents, the SMART is provided with a number of engineered safety features such as the PRHRS.

The PRHRS is designed such that any core damage beyond the specified limits of safe operation is excluded for the first 72 hours following occurrences of the event without operator's actions and external power sources. A brief description of the PRHRS is presented below. The design goal of the PRHRS is to cooldown the reactor to a safe stable condition within 36 hours and to provide the heat removal capability for 72 hours after reactor shutdown. In this paper a modeling for the PRHRS performance analysis is developed and a numerical analysis is performed in order to evaluate the passive heat removal characteristics of the PRHRS.

2. Description of Passive Residual Heat Removal System (PRHRS)

The function of the PRHRS is to remove the decay heat and sensible heat passively by natural circulation in case the normal steam extraction or feedwater supply is unavailable. Passive principle is applied to the PRHRS which consists of four independent trains and any two trains are sufficient to remove the decay heat. The PRHRS is hydraulically connected to SG by piping line. Each train includes a emergency cooldown tank (ECT), a heat exchanger (HX), and a compensating tank (CT). The HX is submerged in ECT filled with water. The CT is intended for filling the system pipelines with water during system cooldown process.

In case the normal steam extraction or feedwater supply is unavailable, the second valves on the main steam and feedwater pipelines, as viewed from the reactor vessel, are closed and the PRHRS is aligned for operation. In the cooldown process, the heat is transferred to the ECT through the HX. The water in the ECT is heated and eventually evaporates into the atmosphere. Water inventory in the tanks is sufficient for 72-hour system operation. The schematic diagrams of analysis model for the PRHRS and for the cold pressurizer are shown in figures 1 and 2, respectively. The major design data of the SMART are shown in Table 1.

Table 1 Major Design Data of SMART

Power	Nominal Thermal Power of the Reactor, MWt	330
Primary system	Pressure in Primary Circuit, Nominal/Design, MPa	15.0/17.0
	Coolant Temperature at Nominal Power Operation, Outlet/Inlet, °C	310.0/270.0
	Coolant Flow Rate via the Core, kg/s	1556.0
	Number of MCPs	4
	Inventory of Primary Coolant, kg	46318.5
Secondary System	Steam Output, kg/s	152.4
	Superheated Steam Pressure/Feedwater, MPa	3.0/5.0
	Superheated Steam/Feed Water Temp., °C	274/190
Reactor Vessel	Height of Reactor Vessel, m^3	10.0
	Inner Diameter of Reactor Vessel, m	2.6
Steam Generator	Diameters of Main Steam /Feedwater Line, m	0.2/0.1
	Outer/Inner Diameters of SG Tube, mm	12.0/9.0
	Average Helicoiling Diameter of SG Tube, mm	470.0
	Active Height of SG/Average Length of One SG Tube, m	2.65/14.4
	Number of SG Cassettes/Number of SG Tubes per One Cassette	12/330
	Lateral/Longitudinal Pitch of SG Tube Bundle, mm	16.5/13.5
	Nominal dP in SG Steam/FW Header due to Local Hyd. Resistance, MPa	0.3/1.0
Pressurizer	Volume of End Cavity(EC)/Intermediate Cavity(IC)/Annular Cavity(AC), m^3	12.46/1,54/7.70
Pressurizer Insulator	Thickness of Insulator in IC, m	.02
	Number of Insulation Layers in IC	20.0
Pressurizer Cooler	Outer/Inner Diameter of Cooler Tube, mm	13.0/10.0
	Number of Tubes	6.0
	Cooler Tube Length, m	19.8
	Cooling Water Flowrate per One Cooler, kg/sec	0.57
Heat Exchanger	Number of HX Tubes per One Section	400
	Outer/Inner Diameter of HX Tube, mm	25.0/20.0
	Length of One HX Tube, m	2.5
PRHRS	Volume of Compensating Tank per Train, m^3	2.56
	Volume of Emergency Cooldown Tank per Train, m^2	52.0
	Diameter of Steam/Water Pipe Line of the PRHRS, mm	100.0/64.0
	Effective Height for Natural Circulation of the PRHRS, m	13.0
	Local Hyd. Resistance of Isolation Valves on Steam Line/Water Line	40.0/12.0

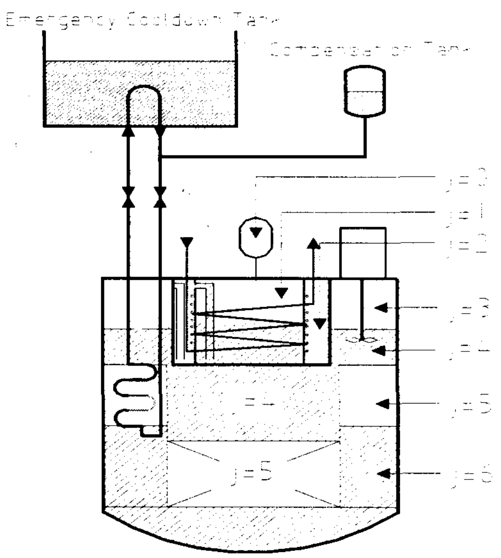

Fig. 1 Schematic Geometry of SMART for Performance Analysis of PRHRS

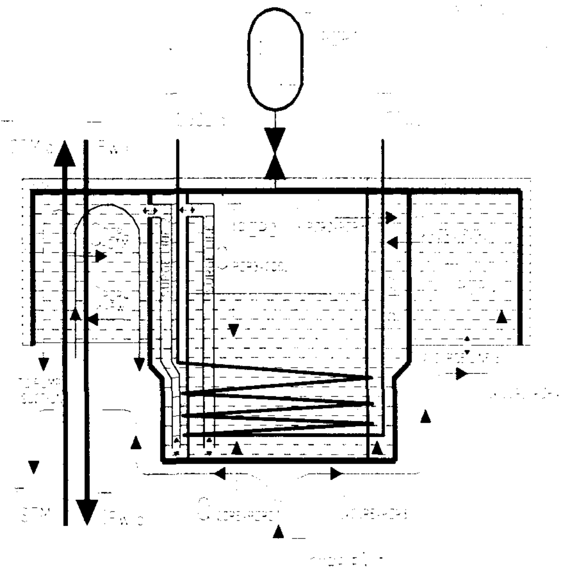

Fig. 2 Analysis Model for Cold Pressurizer

3. Modeling for Performance Analysis of the PRHRS

3.1 Basic Equation

Mass Continuity Equation

$$\dot{m} = \rho_j v_j A_j = \rho_{j+1} v_{j+1} A_{j+1} \tag{1}$$

$\dot{m}$ ρ, v, A are mass flowrate, density, velocity, and cross-sectional area, respectively.

Momentum Equation

$$-\frac{dP}{dl} = \frac{d}{dl}\left(\frac{G^2}{\rho}\right) + \left[K_j \frac{Pe_j}{A_{surj}} + \frac{f}{D} + \xi_i\right]\frac{G^2}{2\rho}\,\eta_{2\Phi} + \rho g \sin\theta \tag{6}$$

where,

$$\xi_i = \frac{0.1}{\pi D_{wind}} \tag{3}$$

$$\eta_{2\Phi} = 0.5\left(\frac{v_{2\Phi}}{v_{1\Phi}} - 1\right) + 1 \tag{4}$$

K_j is an empirical irreversible form loss coefficient. G is mass flux and f is the friction factor for pipe. Pe, l, D are perimeter of tube, flow-directional length, and diameter of tube, respectively. θ is the angle of flow direction relative to the reference coordinate of +z. ξ_i is the correction coefficient for flow in helicoil tube. $\eta_{2\Phi}$ is the correction coefficient to account for the two-phase flow.

Energy Equation

Heat transfer through wall surface heating/heated medium can be quantitatively defined as follows:

$$Q = UA \triangle T_{LMTD} \tag{5}$$

where U is overall heat transfer coefficient, A is heat transfer area, and $\triangle T$ is log mean temperature difference. If there is fluid movement on the wall surface, following additional constraint is added:

$$\frac{dQ}{dz} = \dot{m}\frac{di}{dz} \tag{6}$$

3.2 Nodalization of System for Steady-State Analysis

Nodalizations of calculational regions for analysis are shown in figure 1. cold pressurizer is divided into 3 regions depending on different zones of temperature. Reactor vessel is divided into 3 regions depending on different zones of bulk temperature. Tubes in SG, tubes in HX, and water/steam piping lines in the PRHRS are divided into several small regions. Reactor core is divided into 8 regions according to axial power shapes. In this steady-state analysis, cooling water is assumed to be supplied to pressurizer cooler and water temperature in ECT is assumed to be constant at 60 °C. Core exit temperature is used as the only input parameter for the analysis. Other parameters such as the primary and the secondary natural circulation flowrate, steam temperature, pressure are calculated.

3.3 Modeling of Transient Heat Capacity in Bulk Mass of Primary System

To obtain quasi-steady behaviour of temperature of the bulk mass of interest in primary system, rate of heat generation and rate of heat removal in the primary system must be considered. The rate of quantity of heat added to the bulk mass of interest in primary system is only core decay heat generation rate which is designated as $\dot{Q}_D$. The rate of quantity of heat removed from the bulk mass, $\dot{Q}_{SG}$, is obtained in terms of core exit temperature from steady state heat balance equation described in the preceeding section. Quasi-steady energy equation for the bulk mass can be expressed as follows:

$$\dot{Q}_S = \dot{Q}_D - \dot{Q}_{SG} \tag{7}$$

$$\begin{aligned}\dot{Q}_S &\approx \frac{d}{dt}[\sum_i (M_{Mi}C_{pMi} + M_{Wi}C_{pWi})T_{Wi}] \\ &= \frac{d}{dt}[C_1 \overline{T_1}]\end{aligned} \tag{8}$$

For simplicity of calculation, we assumed that local temperature of metal is the same as that of coolant. $\overline{T_1}$ is the average temperature of the bulk mass. $\overline{T_1}$ and C_1 are defined as follows :

$$\overline{T_1} \approx \frac{\sum_i (M_{Mi}C_{pMi} + M_{Wi}C_{pWi})T_{Wi}}{\sum_i (M_{Mi}C_{pMi} + M_{Wi}C_{pWi})} \tag{9}$$

C_1 is defined as follows:

$$C_1 = \sum_i (M_{Mi}C_{pMi} + M_{Wi}C_{pWi}) \tag{10}$$

4. Results and Discussions

A calculational analysis has been performed assuming that 2 trains of the PRHRS (assuming maintenance and single failure) are in operation. Core exit temperature of 290 ℃ is assumed for the starting temperature. Figures 3 and 4 show the results of the performance analysis of the PRHRS until the time when core exit temperature reaches stable temperature (safe shutdown condition) after reactor shutdown.

Figure 3 shows the trends of core exit temperature, core inlet temperature, steam temperature (fluid temperature at outlet of SG in secondary side), feedwater temperature (fluid temperature at outlet of HX in secondary side), EC temperature, IC temperature, and AC temperature. At the beginning (upto about 30 seconds) core exit temperature rises to about 295 ℃ because the decay heat generation rate is higher than heat removal rate through SG. Afterwards core exit temperature begins to decrease. Superheated steam exits the SG at the beginning of cooldown and the steam quality decreases as the primary coolant is cooled down. At the time of 6900 seconds (about 2 hours), the core exit temperature reaches stable temperature of 215 ℃.

Pressures, natural circulation flowrate, heat removal rate through SG, and water levels are shown in Figure 4. Secondary natural circulation flowrate reaches a maximum value of 8.51 % of nominal at about 2000 seconds, when feed water temperature also reaches its maximum, and then decreases with time. This flow trends are formed mainly by a difference between pressure drop along the flow path and hydrostatic driving force for natural circulation. At core exit temperature of about 218 ℃, water exits the outlet of the steam generator and natural circulation flowrate (and therefore cooldown rate) are decreased due to the reduction of driving force for natural circulation. At core exit temperature of 220 ℃, water level in EC reaches a minimum water level and water level in IC begin to decrease. It is notable that during cooldown process water temperature in EC and IC are stable and its variations are not large. This shows that the performance of the cold pressurizer adopted in the SMART is excellent. Figure 4 also shows trends of pressure in cold pressurizer and in CT. For the time upto about 30 seconds, pressure in pressurizer rises to about 13 MPa due to the temperature increase in core exit, after then pressure in pressurizer begins to decrease as the primary coolant is cooled down. At the time of this cooldown, the pressure in CT rises to the maximum of 5.5 MPa from initial pressure of 4.5 MPa due to high heat flux addition from the primary side, which means during this period there is a reverse flow into CT. Average cooldown rate during cooling process is about 40 ℃/hour.

5. Conclusions

In this study, a computer code for analysing the PRHRS performance for the SMART was developed. The calculational results show that at the time of 6900 seconds (about 2 hours) after reactor shutdown, the core exit temperature reaches stable temperature of 215 ℃ and average cooldown rate of primary coolant during cooldown process is about 40 ℃/hour. It is also notable that the variation of water temperature and pressure in cold pressurizer is smooth during cooldown process. The results of the performance analysis of the PRHRS show that the PRHRS of the SMART has excellent passive heat removal characteristics under the assumptions that pressurizer cooler is available and water in ECT is constant at 60 ℃. From these results, it is preliminarily concluded that the passive cooling concept using the PRHRS of the SMART is feasible. However, the analysis under the elimination of these assumptions may be a more limiting case and thus a further development of analysis modeling is needed.

References

[1] Seo, J. K., et al., *Advanced Integral Reactor (SMART) for Nuclear Desalination,* IAEA Symposium on Desalination of Seawater with Nuclear Energy, IAEA-SM-347/40, May 1997,

[2] Seo, J. K., et al., *Steady-State Performance Analysis of Pressurizer and Helical Steam Generator for SMART,* Proceedings of KNS Spring Meeting, Kwangju, Korea, May 1997,

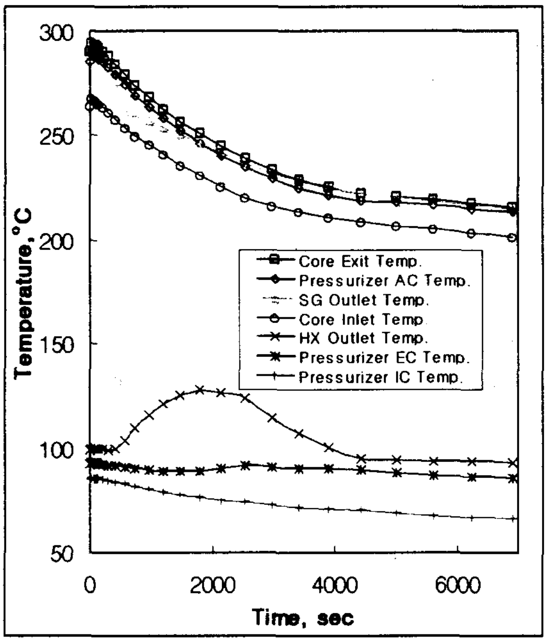

Fig. 3 Temperature Trends with Time after Reactor Shutdown

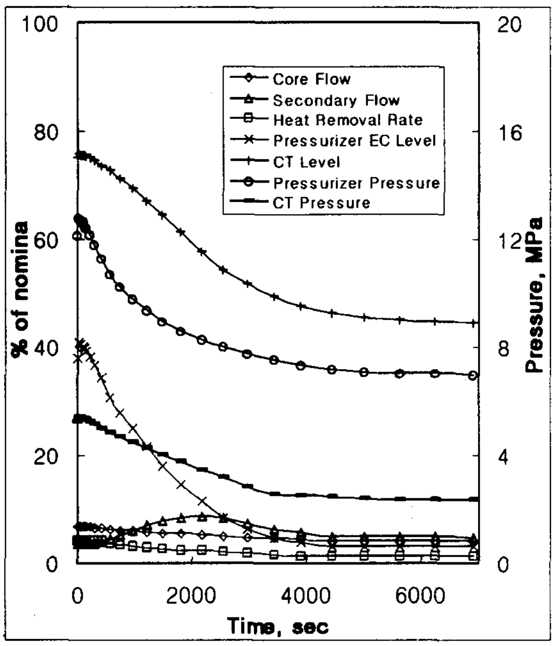

Fig. 4 Trends of Pressure, Level, Flow, and Heat Removal Rate with Time after Reactor Shutdown